APPARATUS FOR AND METHOD OF COOLING AND POSITIONING A TRANSLATING SUBSTRATE TAPE FOR USE WITH A CONTINUOUS VAPOR DEPOSITION PROCESS

FIELD OF THE INVENTION

The present invention relates to high-throughput IBAD systems. More specifically, the present invention relates to a substrate cooling and support structure that positions and removes heat from a translating metal substrate tape as the tape translates through a deposition zone of such a length that characterizes high-throughput IBAD systems.

BACKGROUND OF THE INVENTION

Wire forms the basic building block of the world's electric power system, including transformers, transmission and distribution systems, and motors. The discovery of revolutionary high-temperature superconducting (HTS) compounds in 1986 led to the development of a radically new type of wire for the power industry; this discovery is the most fundamental advance in wire technology in more than a century. However, to date only short samples of the HTS tape used in the manufacture of next-generation HTS wires have been fabricated at high performance levels. In order for HTS technology to become commercially viable for use in the power generation and distribution industry, it will be necessary to develop techniques for continuous, high-throughput production of HTS tapes.

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Ion beam-assisted deposition (IBAD) has become a convincing candidate for enabling the cost-effective high-throughput thin film growth necessary to realize widespread adaptation of superconducting materials in the electricity transmission/distribution industry. IBAD is described in U.S. Patent No. 6,258,472, entitled "Product having a substrate of a partially stabilized zirconium oxide and a buffer layer of a fully stabilized zirconium oxide, and process for its production." IBAD has been shown to be particularly well suited for depositing the buffer layers such as of yttrium-stabilized zirconia (YSZ) and cerium oxide (CeO_2) that serve as a support for a functional layer of a ceramic superconducting material, such as yttrium-barium-copper-oxide (YBCO), atop the buffering layers

During IBAD, a vacuum-deposition process occurs that combines physical vapor deposition (PVD) with ion beam bombardment. A vapor of coating atoms is generated with an electron beam evaporator and deposited on a substrate such as a translating metal tape. Ions are simultaneously extracted from a source and accelerated into the growing PVD film at energies of a few hundred electron-volts (eV). The ions impart substantial energy to the coating and coating/substrate interface, driving the depositing species into the substrate and enhancing adhesion by producing a graded material interface. These factors combine to enable the deposition of uniform, adherent, low-stress buffer layer films ideal for subsequent superconducting thin film deposition. . In addition, concurrent ion beam bombardment of a growing film has been shown to impart biaxial texture. IBAD has been specifically used for this purpose to achieve a high-degree of biaxial texture in materials used as buffer layers for HTS tapes.

While prior art IBAD processes, such as described in Neumuller, et al., USP 6,258,472, dated July 10, 2001 and entitled Product Having A Substrate Of A Partially Stabilized Zirconium Oxide And A Buffer Layer Of A Fully Stabilized Zirconium Oxide, And Process For Its Production are well known for their uniform and adherent thin film qualities, they are limited in the throughput they can achieve, and thus fail to produce HTS material in the cost-effective manner necessary to enable the widespread adaptation of such materials in the electricity transmission/distribution industry. Key to enabling a high-throughput system is the achievement of a large deposition zone. The size of the deposition zone determines the area onto which thin film deposition atop a substrate may occur. Consequently, an IBAD system characterized by a long deposition zone may enable metal substrate tapes to translate through the system and receive an optimum thin film deposition at velocities sufficient to achieve desirable throughput levels. However, innovations must be made to accommodate increased deposition zone lengths before a high-throughput IBAD system can be realized, including ways to optimally position, monitor, and maintain the temperature of the tape as it traverses the entire length of the deposition zone.

Such a translating substrate tape must be maintained at a precise angle relative to the impinging ion beam throughout the entirety of the deposition zone to ensure proper film properties. Any flex experienced by the tape causes the angle between the tape and the ion beam to change and regions of compromised thin film uniformity to develop.

The long deposition zone that characterizes a high-throughput IBAD system presents significant tape-cooling issues not present in systems with smaller deposition

zones, such as described in Neumuller, et al. The deposition process induces heat in the tape that must be removed to stabilize the deposited films. This heating can raise the tape temperature to levels at which the product becomes unusable due to degrading effects on the deposited film. Existing cooling techniques utilize simple conduction to remove excess heat from substrates and are ineffective for high-throughput IBAD systems because the translational motion of the tape reduces the thermal contact between the tape and the cooling structure, causing erratic cooling.

Further, it is desirable to monitor the temperature of the tape and the substrate support temperature at different points throughout such a long deposition zone in order to obtain feedback about how deposition is proceeding and in order to enable process parameters to be adjusted to optimize the process. However, it is desirable to make such measurements without making physical contact with the translating tape, as any motion between the tape and a conductive temperature-sensing device reduces thermal contact and results in inaccurate temperature readings.

It is therefore an object of the invention to provide a substrate assembly for use in high-throughput IBAD systems that is capable of optimally positioning a translating substrate tape throughout the entirety of the long deposition zone associated with such a system.

It is yet another object of the invention to provide a substrate assembly for use in high-throughput IBAD systems that is capable of maintaining a translating substrate tape at an optimum deposition temperature throughout the entirety of the long deposition zone associated with such a system.

It is yet another object of the invention to provide a substrate assembly for use in high-throughput IBAD systems that allows in situ tape temperature measurement without a temperature-sensing device making physical contact with the tape.

BRIEF SUMMARY OF THE PRESENT INVENTION

The present invention is an apparatus for and method of cooling and positioning a translating substrate tape. The substrate tape comes into contact with the apparatus, hereafter referred to as a substrate assembly, as it translates the length of the deposition zone of a high-throughput IBAD or other coating system. A chilled liquid passes through internal passages of the substrate assembly, maintaining the temperature of the substrate assembly below a specified level. Also passing through internal channels in the substrate assembly is an inert gas that exits at an interface between the translating tape and the substrate assembly. The thermal contact between the substrate assembly and the tape results in conductive cooling of the tape, while the flow of gas against the tape induces convective cooling. The substrate assembly is of sufficient length to maintain the tape at a desired position with respect to the impinging ion beam throughout the entire length of the deposition zone to ensure optimum film properties.

The substrate assembly further includes a sapphire waveguide in communication with a pyrometer. The waveguide provides an optical pathway for infrared (IR) temperature measurements of the non-exposed side of the translating substrate tape without making physical contact with the tape.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a high-level block diagram of an IBAD system.

Figure 2 illustrates a front view of an IBAD chamber assembly apparatus.

Figure 3A is a first cross-sectional view of the substrate assembly taken along line A-A of **Figure 2.**

Figure 3B is a second cross-sectional view of the substrate assembly taken along line B-B of **Figure 3A.**

Figure 4A illustrates a side view of a first embodiment of the substrate block portion of the substrate assembly of the present invention.

Figure 4B illustrates a side view of a second embodiment of the substrate block portion of the substrate assembly of the present invention.

Figure 5 illustrates a method for cooling a substrate assembly and a translating metal tape.

DETAILED DESCRIPTION OF THIS INVENTION

Figure 1 illustrates a high-level block diagram of an IBAD system **100** in accordance with the invention, depicting the functional relationships between each subsystem. The IBAD system **100** includes a plurality of subsystems as follows:

An IBAD chamber assembly **134** that includes an IBAD chamber and other elements. The IBAD chamber assembly **134** is described in detail in reference to **Figure 2.**

A gas delivery system **110** that provides gas through a gas line **116** and a valve **118** to the IBAD chamber assembly **134** at a desired flow rate to meet process

specifications. The gas line **116** may include one or more separate pathways for different gases.

A vacuum pump system **120** that is a commercially available vacuum pump and associated equipment capable of drawing air or other gases from the IBAD chamber assembly **134** through a vacuum connector **122**, and maintaining a vacuum pressure of the order of magnitude of 10^{-5}, preferably 10^{-7} Torr. One example of such a pump is an APD Cryogenics, Marathon 16 cryopump.

A chiller **136** that is a standard refrigeration device through which liquid refrigerants flow. Such liquids may include deionized water, deionized water with glycol, and liquid nitrogen. A refrigeration loop is created between the chiller **136** and the IBAD chamber assembly **134** via a coolant line-in **140** and a coolant line-out **142**.

A reel-to-reel transport system **132** that is a spooling system that serves to translate a length of metal substrate tape in a linear fashion through the IBAD chamber assembly **134** while maintaining optimum tape tension, position, and speed. The reel-to-reel transport system **132** is connected through the IBAD chamber assembly **134** via a mechanical connector **114**.

Lastly, the IBAD system **100** includes a controller **126** with a plurality of inputs and outputs that meet the requirements of the peripherals described in reference to **Figures 1** and **2**. The controller **126** may be one or more micro-controllers or a PC with appropriate hardware and software. The controller **126** is electrically coupled to and provides control to the gas delivery system **110** via a connector **112**, to the vacuum pump system **120** via a connector **124**, to the chiller **136** via a connector **138**, to the reel-to-reel

transport system **132** via a connector **128**, and to elements of the IBAD chamber assembly **134** described in reference to **Figure 2** via a connector **130**.

In operation and in continuing reference to **Figure 1**, the controller **126** operates the vacuum pump system **120** through the connector **124**, evacuating the IBAD chamber assembly **134** through the vacuum connector **122**. The controller **126** then operates the gas delivery system **110** through the connector **112**, delivering controlled levels of ambient gas through the gas line **116** and the valve **118** to the IBAD chamber assembly **134**. Through the connector **128**, the controller **126** operates the reel-to-reel transport system **132**, which, in turn, controls the tape transport through the IBAD chamber assembly **134** through the mechanical connector **114**. The controller **126** communicates through the connector **130** to operate elements within the IBAD chamber assembly **134**, as described in reference to **Figure 2**.

The controller **126** communicates through the connector **138** to operate the chiller **136**. The chiller **136** cools down a liquid refrigerant, and the refrigerant flows into the IBAD chamber assembly **134** through the coolant line-in **140**. Warmer liquid returns from the IBAD chamber assembly **134** through the coolant line-out **142** to be recycled through the chiller **136**.

Figure 2 illustrates a front view of the IBAD chamber assembly **134**. As this view shows, the IBAD chamber assembly **134** further includes an IBAD chamber **210** that is a pressurized vacuum chamber. The IBAD chamber **210** may be constructed of any non-corroding metal, such as 304 stainless steel. The IBAD chamber **210** includes

all the necessary gaskets, seals, and seal plates to maintain a vacuum to the order of 10^{-5}, preferably10^{-7} Torr.

As shown in **Figure 2**, the vacuum pump system **120** connects via the vacuum connector **122** disposed in the outer wall of the IBAD chamber **210**. This arrangement evacuates the IBAD chamber **210** to approximately 10^{-7} Torr.

A substrate assembly **220**, which is described in detail in reference to **Figures 3** and **4**, is suspended in the IBAD chamber **210** such that a deposition zone is created at the surface of the substrate assembly **220**. A tape **228** comes into contact with and translates in a linear fashion underneath the substrate assembly **220** via the action of a payout spool **218** and a take-up spool **222** of the reel-to-reel tape transport system **132**, which may or may not be disposed inside the IBAD chamber **210**. The payout spool **218** is a spool from which the tape **228** unwinds as the tape **228** translates through the IBAD chamber **210**. The take-up spool **222** is the spool onto which the tape **228** winds subsequent to undergoing the IBAD process. The diameter and width of the payout spool **218** and the take-up spool **222** may vary with the dimensions of the desired product and are constructed from a variety of materials capable of withstanding vacuum chamber conditions. Other elements (not shown) of the reel-to-reel tape transport system **132** control the tape speed, tension, and position as the tape **228** translates through the IBAD chamber **210**. Additionally, a strain gauge **230** is disposed so as to make contact with the tape **228**. The strain gauge **230** is a sensing device capable of measuring the tension in the tape **228** and is well known to the art.

The tape **228** is an extended length of substrate formed from a variety of metals, such as stainless steel or a nickel alloy such as Inconel. The tape **228** is capable of withstanding temperatures up to 900 °C. The dimensions of the tape **228** may vary to meet the desired finished product and system limitations. For example, the tape **228** may have a thickness of 25 microns, a width of 1 cm, and a length of 100 meters.

A gas inlet **212**, a gas inlet **214**, and a gas inlet **216** are disposed through the outer wall of the IBAD chamber **210** and are fed by the gas delivery system **110** via the gas line **116**. The gas inlets **214** and **216** open into the IBAD chamber **210**, while the gas inlet **212** connects directly to the substrate assembly **220**. Consequently, three separate, sealed gas flow lines are formed between the gas delivery system **110** and the IBAD chamber **210**.

Also disposed within the IBAD chamber **210** is an electron-beam (e-beam) evaporator assembly **232** horizontally aligned with the center of the substrate assembly **220**. The e-beam evaporator assembly **232** is an apparatus that vaporizes material from a cylinder of solid material by means of electron beam heating, as is well known to the art.

Other energy sources, such as magnetron or ion-beam sputtering sources, (not shown) may be used to vaporize the coating material instead of the electron-beam source.

Further, an ion beam source **224** is disposed within the IBAD chamber **210** in such a manner that a beam of ions (not shown) emitted therefrom is directed toward the tape **228** at an incident angle of, for example, 55 degrees. The ion beam source **224** is a commercially available ion gun that directs a stream of positive ions at the tape **228** to bombard the material embedded on the tape **228** as it accumulates by vapor deposition.

In operation and in continuing reference to **Figure 2**, the IBAD chamber **210** is evacuated by the vacuum pump **120**. The gas inlets **212, 214**, and **216** funnel gas into the IBAD chamber **210**. The reel-to-reel transport system **132** mechanically rotates the payout spool **218** and the take-up spool **222**, thereby translating the tape **228** over the substrate assembly **220** at speeds between 0.5 to 100 meters per hour. The tape **228** is within the deposition zone of the IBAD system **100** as it translates across the substrate assembly **220**. Within the deposition zone, a buffer layer such as cerium oxide (CeO_2) or yttria-stabilized zirconium (YSZ) is deposited atop the tape **228** as material evaporated from the e-beam evaporator assembly **232** and ions emitted from the ion beam source **224** impinge upon the tape **228**. The tape **228** contacts the strain gauge **230** prior to winding onto the take-up spool **222**, and a tension measurement is made.

Figure 3A is a first cross-sectional view of the substrate assembly **220** taken along line A-A of **Figure 2**. This view shows that the substrate assembly **220** further includes a substrate block **314** having a coating **322** such as YSZ covering outer surface of the substrate block **314**. Within the substrate block **314** is disposed a coolant channel **320** having a coolant inlet **310** and a coolant outlet **312**. The coolant channel **320** is a metal pipe that runs through a channel in the partition blocks. The coolant channel **320** may be the single U-shaped pipe illustrated. The coolant channel **320** may also be shaped in multiple other ways, such as a curved pipe that runs in alternating directions, to increase the inner surface area of the substrate block **314** that contacts the coolant channel **320**.

The substrate assembly **220** further includes a plurality of gas holes **316** and a sapphire waveguide **318**, which is a sapphire optical fiber that is transparent to infrared wavelengths.

Figure 3B is a second cross-sectional view of the substrate assembly **220** taken along line B-B of **Figure 3A**. The cross-sectional view of **Figure 3B** is perpendicular to the cross-sectional view of **Figure 3A**. This view shows that the substrate assembly **220** includes the substrate block **314**, through which is disposed a gas inlet **324** (fed by the gas inlet **212**) that branches into multiple rows of multiple gas holes **316**, each of which are approximately 0.025 to 0.4 mm in diameter and terminates in one of a plurality of orifices or nozzles **340** disposed through a bottom edge **338** of the substrate block **314**. The substrate block **314** is further shown to include a manifold header **328**, a partition **330**, a partition **332**, and a partition **334**. alternatively, partitions **332** and **334** may be replaced by a unitary block [not shown]. The manifold header **328** is a metallic, preferably copper,m block placed on top of the partition **330**; a cavity machined in the manifold header **328** covers all the gas holes **316**. Each gas hole **316** is drilled completely through the partitions **330**, **332**, and **334**. The partitions **330**, **332**, and **334** are metallic, preferably copper, blocks stacked on top of one another to form the structure of the substrate block **314**. A pyrometer **326** is shown optically connected to the sapphire waveguide **318**. The controller **126** is in communication with the pyrometer **326** and one or more thermocouples **336**. The pyrometer **326** is a standard optical pyrometer for measuring temperature. The thermocouples **336** are standard transducers used for temperature measurement.

The bottom edge **338** on the partition **334** is rounded in the plane shown in **Figure 3B** to a radius of curvature of about 20 feet to allow the tape **228** to be positioned against the bottom edge **338**.

In operation, an inert gas from the gas delivery system **116**, such as nitrogen, argon, or helium, enters through the gas inlet **212** that subsequently feeds the gas inlet **324** and proceeds to the manifold header **328**. The manifold header **328** distributes the gas evenly into all the gas holes **316** and the gas proceeds out the orifices or nozzles **340**. The gas forms a cushion over which the tape **228** translates. This gas flow pattern reduces contact between the tape **228** and the bottom edge **338**, thus enhancing heat removal from the tape **228**. The expansion of gas as it issues forth through the orifices of nozzles **340** further cools the gas and enhances heat removal from the tape **228**. The gas flow is kept to a flow pressure of less than one standard cubic centimeter per minute (SCCM). The radius of curvature of the bottom edge **338** is sufficiently large that the tape **228** maintains the correct angle with respect to the ion beam source **224**.

In an alternative embodiment of the invention the inert gas is replaced in whole or in part by oxygen.

In yet another embodiment of the invention, two separate gas systems are utilized; one supplying inert gas, the other oxygen.

Simultaneously, liquid coolant from the chiller **136** flows through the coolant line-in **140**, into the coolant inlet **310**, through the coolant channel **320**, out the coolant outlet **312**, through the coolant line-out **142**, and back to the chiller **136** to be recycled through the coolant system. The cooling effect of the liquid from the chiller **136** and the

gas flow through the substrate assembly **220** and out the orifices or nozzles **340** maintains the temperature of the substrate block **314** within specifications, e.g., below 50 °C.

Infrared radiation from heat at the bottom edge **338** travels upward through the sapphire waveguide **318** and enters the pyrometer **326**. The pyrometer **326** measures the radiation carried by the sapphire waveguide **318** and transmits that information in the form of a temperature at the bottom edge **338** to the controller **126**. In the same way, the thermocouples **336** transmit temperatures to the controller **126** from various locations on the substrate assembly **220**, ensuring that no part of the substrate block **314** is overheating. The controller **126** can then adjust the controls in the chiller **136** to raise or lower the temperature of the liquid coolant, alter the flow rate of the liquid coolant, or alter the flow of the gas to keep the temperature of the substrate block **314** within specifications.

Figure 4A illustrates a side view of a first embodiment of the substrate block **314** of the substrate assembly **220** of the present invention. In the side view of the substrate block **314** illustrated in **Figure 4A**, the substrate assembly **220** includes all the components shown in **Figures 3A** and **3B**; however, some have been omitted from **Figure 4** for clarity. **Figure 4A** includes the substrate block **314**, the orifices or nozzles **340**, the tape **228**, and a channel **410**. **Figure 4B** includes the substrate block **314**, the orifices or nozzles **340**, the tape **228**, the channel **410**, a tab **412**, a tab **414**, an inner surface **416**, and an inner surface **418**.

In the substrate block **314** of **Figure 4A**, the channel **410** is cut to a width slightly larger than the width of the tape **228**. One or more additional orifices or nozzles **340** can

be cut into the sides of the channel **410**, as shown in **Figure 4A**. The tape **228** is accommodated in the channel **410**, which keeps the tape **228** centered on the substrate block **314**. In addition, when the tape **228** is accommodated in the recessed channel **410**, less gas exiting the orifices or nozzles **340** leaks into the IBAD chamber **210**, while maintaining sufficient pressure to keep the tape **228** separated from the bottom edge **338**. Therefore, there is less ambient gas interfering with ions issued from the ion beam source **224** and directed at the tape **228**.

Figure 4B illustrates a side view of a second embodiment of the substrate block **314** of the substrate assembly **220** of the present invention. **Figure 4B** illustrates a variation of the substrate block **314** in which tabs **412** and **414** are attached to or machined from the substrate block **314**. The inner surfaces **416** and **418** of the tabs **412** and **414**, respectively, are coated with Teflon™ or a similar substance to decrease friction with the tape **228**, which is pushed against the Teflon™ surface by the pressure of the gas exiting the orifices or nozzles **340**. This embodiment provides an even better gas seal for the purposes stated above. The tabs **412** and **414** are small enough so as not to obstruct the ions from impinging on the tape **228.**

Figure 5 shows a method **500** for cooling the substrate assembly **220** and the translating tape **228** using a liquid coolant flow and gas convective thermal transfer, in accordance with the invention. The method **500** starts at the same time and runs concurrently with the process that runs the entire IBAD system **100**. The method **500** includes the following steps:

Step 510: Setting chiller temperature

In this step, an operator or the controller **126** sets the initial temperature of the liquid coolant that maintains the temperature of the substrate block **314** within specifications.

Step 515: Setting coolant flow rate

In this step, the operator or the controller **126** sets the flow rate of the liquid coolant that maintains the temperature of the substrate block **314** within specifications.

Step 520: Setting gas flow rate

In this step, the operator or the controller **126** sets the gas flow rate through the substrate block **314**, the gas holes **316**, and the orifices or nozzles **340**. The rate is high enough to maintain a cushion of gas between the tape **228** that is translating in a linear fashion and the bottom edge **338**, and is lower than one SCCM.

Step 525: Monitoring thermocouples

In this step, the operator, in conjunction with the controller **126**, monitors the surface temperature of the substrate block **314** to ensure that the temperature throughout the substrate block **314** is within specifications.

Step 530: Monitoring pyrometer

In this step, the operator, in conjunction with the controller **126**, monitors the temperature of the bottom edge **338** with data from the pyrometer **326** to ensure that the temperature is within specifications.

Step 535: Monitoring tape tension with strain gauge

In this step, the operator, in conjunction with the controller **126**, monitors the tension on the translating tape **228** from data gathered by the strain gauge **230**. If the

tension is too high, the tape **228** could stretch or break; if the tension is too low, the tape **228** can sag too far from the substrate block **314**.

Step 540: Temperatures within specifications?

In this decision step, the operator or the controller **126** determines whether all temperatures measured by the pyrometer **326** and/or the thermocouples **336** are within specifications, typically less than 50 °C. If so, the method **500** proceeds to step **550**; if not, the method **500** proceeds to step **545**.

Step 545: Adjusting cooling parameters

In this step, the operator or the controller **126** adjusts the thermostat on the chiller **136**, the liquid coolant flow rate, the gas flow rate, or any combination of these three to bring the temperature of the substrate block **314** back to within specifications.

Step 550: Tape tension within specifications?

In this decision step, the operator or the controller **126** determines whether the tension of the translating tape **228** is within specifications. If so, the method **500** proceeds to step **560**; if not, the method **500** proceeds to step **555**.

Step 555: Adjusting tape tension

In this step, the operator or the controller **126** adjusts the tension of the translating tape **228** to within specifications using various means, such as adjusting the torque of the take-up spool **222**.

Step 560: Process finished?

In this decision step, the operator or the controller **126** determines whether the method **500** is finished, based on criteria that may include the length of tape **228** collected

by the take-up spool **222**, the length of time that the IBAD system **100** has continually run, or other process engineering parameters. If it is decided that the method **500** is finished, the method **500** ends; otherwise, the method **500** returns to step **525**.